

Service-Oriented Architectures, Network-Centric Warfare, and Agile, Self-Synchronized C2: Impacts to Data Fusion Process Design

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ABSTRACT

One of the primary if not the central motivating rationale for Network-Centric Warfare (NCW) is that NCW provides an enabling mechanism for information sharing and shared understanding and awareness of military situations of interest, that in turn allows the realization of entirely new concepts of C2 that are advertised as providing greatly increased agility, speed of command, and synchronization in C2. In turn, the underlying enabling “IT” mechanism for NCW is the Service-Oriented Architecture (SOA) concept, within which all functional services, to include Data Fusion Services, will presumably operate. These attractive but as-yet-not-fully-defined concepts represent a challenge to the Data Fusion community in terms of understanding the implications of the evolving NCW, SOA, and new C2 concepts on the design of Data Fusion Services. Key to this understanding in particular is the need for a close dialog with the C2 research community on exactly what the information needs of new C2 concepts will be and how those needs can best be met by appropriately-designed Data Fusion Services. This talk will address each of these issues and argue for the need for both: (1) a multi-community approach to the architecting of effective and efficient SOA’s, and (2) for new initiatives in distributed Data Fusion to address the specific technical challenges of NCW-specific Data Fusion Service design and implementation. (It should be noted that this paper is drawn largely from US literature and so presents a US-based viewpoint developed by the author; the paper does not represent any official US governmental views.) This brief paper is intended to sketch the topical areas that will be addressed in the associated Keynote speech.

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Motivation: Network-Centric Warfare (NCW)

In Ref 1, the tenets of Network Centric Warfare are described diagrammatically as follows:

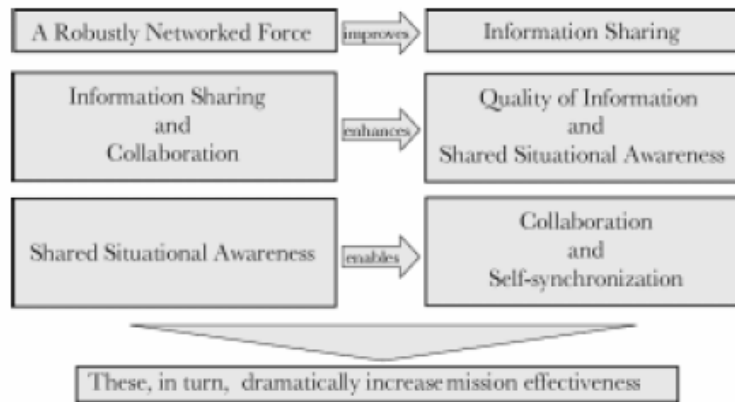


Fig. 1 Tenets of Network Centric Warfare (from Fig 12 of Ref 1)

Or, in words, that a force structure that has an enabling capability for information sharing will realize the benefits of improved quality of information and also of improved situational awareness (ie individual or what could be called “nodal” awareness when considering the force as a networked system), and that the netted environment in turn allows for collaboration, self-synchronization, and shared situational awareness---and that these informational benefits ultimately lead to “dramatically improved mission effectiveness”. Implicit in these tenets is that the people involved will be empowered to act based on the above informational benefits and an awareness of the commander’s intent for the mission/tasks at hand. Most warfare tasks will require collaboration among people from different operational groups (often called “communities of practice”¹); these interacting communities of practice in turn form a “community of interest” or COI². The COI’s are characterized as “evolving” and form dynamically to address the changing needs of the battlespace; ie they are self-organizing and emergent. It is this quality that, in conjunction with the other features above, gives rise to the asserted agility in responsiveness seen in the NCW literature.

The enabling mechanism for information sharing is the Global Information Grid or GIG, that has its roots in the US in the Clinger-Cohen Act (Ref 4) that was a law designating that the US defense establishment should have a “single, end-to-end information system capability that includes a secure network environment, allowing DoD users to access shared data and applications, regardless of location and supported by a robust network/information-centric infrastructure”. Building on this authorization, the technical communities in the DoD developed the GIG concept, one central part of

¹ “communities of practice” are (Ref 2) groups of people linked together by “commitment and identification with the expertise that forms the basis of their practice”—ie they are a group of experts in a domain or task area

² “communities of interest” are *collaborative* groups of users who must exchange information in pursuit of their shared goals, interests, missions, or business processes. (Ref 3)—ie they are multidisciplinary in nature.

which is the Network Centric Enterprise Services (NCES)” capability; NCES is a collection of fundamental services that allow informational and functional interactions and sharing. As the name implies, NCES is grounded on a “Service-Oriented Architecture” or SOA design concept. There is a considerable literature on SOA’s that describe their features and benefits; the SOA concept is the latest preferred architectural approach that has evolved from the computer science/software engineering communities after some four decades of evolution of such design concepts. In this approach, functional capabilities are made available to users as “services” that interact through the use of the core enterprise services that include security control, messaging, and “discovery” services that allow users to become aware of available services. In this milieu, any Data Fusion (DF) capability will also be provided as, and designed as, a service. This, one fundamental impact of operating in the NCW context is that a functional capability such as DF will have to be designed to operate in the SOA environment. While accomplishing this for any specific application context will not be trivial, it seems that the computer science/software engineering communities have been addressing these design questions with considerable energy, and that much guidance will be available to enable such service-based designs to be realized.

There are nevertheless some SOA-based design questions that still loom important for any functional capability, including DF. One of these is the notion of “dynamic composability”, in which, in an SOA architecture, a user can construct a tailored version of a service capability suited to the specific needs of the moment. To achieve this would seem to require that the “granularity”, ie the specificity of the structure of DF service components, be designed so that the user can thread together only those components needed for the task at hand. To do so will require that the DF Service designer understand and anticipate a range of user needs across some application domain, eg a mission or task-set domain so that the developed design can provide the necessary capabilities in such a “problem space”. This type of design challenge is one motivation for the DF community to work toward understanding how COI’s will function in NCW and what their informational needs will be. Additionally, in spite of the apparent flexibility of an SOA, in most military-application cases not all enterprise services will be available all the time to respond (in real-time) to all functional-service demands. This means that in general any functional service will have to understand how such cases will arise and develop contingency-processing strategies to handle these conditions. For example, for a DF Service, it may be possible that at some point communication (via NCES services) to a Sensor Service is not available; the DF Service will require some strategy to handle such delays etc.

Communities of Interest

The COI concept for NCW and the GIG/NCES characterizes COI’s as having four types of structure, depending on how they operate and what they do; these types are shown in the figure below, from Ref 5.

Expedient	Tactically driven, Implied authority, Formal processes modified for need, Relatively many entities (e.g., New Imagery Analysis capability for Damage Assessment)	Tactically driven, Derived authority, Ad hoc processes, Many entities (e.g., Forward deployed JTF planning New Threat Response)
	Explicitly recognized, Longer term, More formalized processes based on span of control, Relatively few entities (e.g., PSAs such as Logistics)	Explicitly or implicitly recognized, Longer term but priority driven, Blended processes resulting from agreements (e.g., JS area such as Battlespace Awareness)
Institutional	Functional	Cross-Functional

Fig 2. Types of COI's (from Ref 5)

It can be seen that COI's will have a range of operational and functional characteristics; importantly, this means that their informational needs will be diverse in accordance with these differing characteristics, meaning that the DF Services supplying information to these COI's may need to be designed differently so that certain types of qualities are achieved for each COI type.

COI Information Needs

At least one key COI that will be serviced by DF is the Command and Control (C2) COI. The information needs of a C2 COI will be specified at least to some degree in what are called "Mission Capability Packages (MCP)" (Ref 6). Developing an MCP begins with a clearly defined mission or set of missions and seeks to define a) what is required to meet the mission(s) successfully and b) how those requirements may differ from the current force structure, command and control arrangements, organizations, doctrine, and technologies. This process is evolutionary and initial MCP concepts are developed in the concept development phase based on prior research, lessons learned, and expert judgment. The evolutionary MCP approach calls for exposing the MCP concept to review and critique by the operational community and domain experts early and often in order to refine and improve the concept. This review may take the form of demonstrations, experiments, exercises, simulations, modeling, or expert criticism. Consequently, it seems quite appropriate that DF Service designers become involved with or at least aware of how any MCP's are being developed that would have informational requirements dependent on DF capabilities; this is another effect of NCW on the DF Service design process.

Complex Adaptive Systems

The above characteristics of COI's (Fig 2) show that they will generally have emergent, self-organizing properties, be quite adaptive, be controlled locally, and exhibit possibly non-linear interactions. These types of properties are among the properties of complex adaptive systems (CAS), suggesting that COI's should be viewed in this context. More specifically, it can be argued that to realize the asserted C2 benefits and tenets of NCW for modern warfare, considered more complex and dynamic than traditional warfare (see Ref 7 for example), a correspondingly-complex type of control paradigm must be invoked. The so-called "Law of Requisite Variety" in cybernetics (Ref 8) can be invoked in this argument, that says that to properly control such a system, the variety of the controller function (the number of accessible states which it can occupy) must match the variety of the combat system itself. In other words, the control system itself, here the C2 COI organization, has to be complex, with great agility. This has then another impact on DF Service design: to understand how CAS's work and what their informational needs are to function effectively.

Dynamics in NCW

Achieving the benefits of C2 and military operations in general of operating in an NCW context is strongly dependent on, and seems to begin with, the notion of information sharing among people. Sharing in turn implies interaction, minimally to send messages but this can also mean sharing beliefs, mental models, interpretations, preferences, and choices for deciding and acting. We see two interacting and important dynamic loops in these interactions: people-to-people, and people-to-automated systems, to include DF processes. Operating within a context of commander's intent, these dynamic processes intersect and together yield (hopefully) the emergent, agile properties of time-critical effective action-taking and effects-producing operations that the NCW vision allows. An additional impact foreseen in order to realize these benefits as regards the people-to-automated systems interaction is that that interaction needs to be of a mixed-initiative type, allowing human intelligence to not only control a passive/responsive type automated capability but to modify the operating knowledge of that automated capability. Such advances in the design of DF Services are seen as not only desirable but necessary to achieve the type of agility envisioned for the NCW environment.

Research and Development

From our reviews of available literature to date, it seems that there has been a limited degree of holistic type research and development on the COI/CAS-side of the NCW paradigm. Of course, a concept like NCW will take some considerable time to be realized in the full operational sense, but we would argue that the realization of that vision is more dependent on the people-side of NCW than on the GIG/NCES side. Moreover, if the CAS argument is accepted then there is a need to develop the design knowledge that will allow CAS capabilities to be developed that have predictable or at least bounded behaviors (since CAS's can also exhibit pathological/chaotic behaviors). Most of the R&D in this area to date has been with the aid of agent-based techniques, which is of course helpful and insightful, and also cost-effective, but there is a lack of validation and R&D on human-based equivalents, using real people in experimental settings to learn the design knowledge to construct

COI's that indeed achieve the desired "NCW-like" performance. Further, recent literature has shown that if formal, statistically-validated experimentation and results-analysis is desired as a framework to study these processes and behaviors, serious thinking has to be applied to develop cost-effective test and evaluation strategies that also yield statistically-valid results.

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Service-Oriented Architectures, Network-Centric Warfare, and Agile, Self-synchronized C2: Impacts to Data Fusion Process Design

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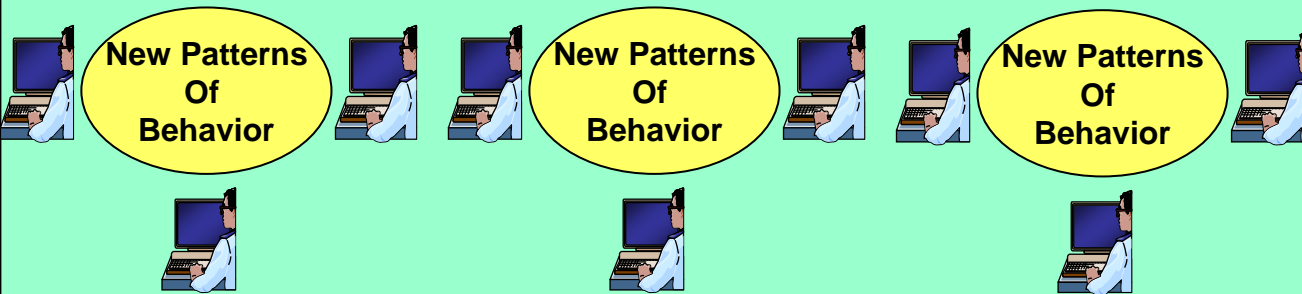
What this talk is

- An individual opinion/point of view about **Basic Research needs** regarding :
 - The specification and design of Data Fusion capabilities that operate in a Network-Centric Warfare / Network-Enabled Capability environment
 - (A U.S.-based view)

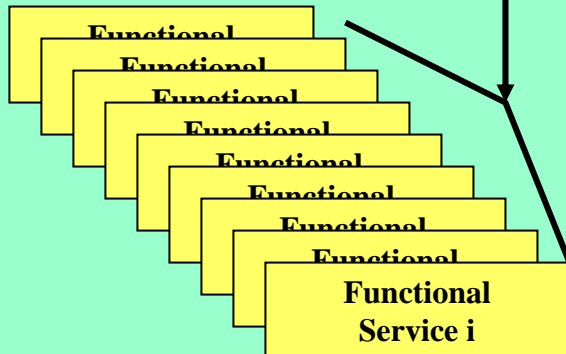
What this Talk is About

**Improved, Agile Warfighting
And Mission Effectiveness**

“Communities of Interest”



**SOA Overarching Framework for Interconnection
--Basic “Enterprise” Services--**



**Data Fusion Functional
Service i**

NCW

**New Ways of :
-Fctl design
-Dec-Mkg
-Analysis
-Assessment**

?

**Impacts to
DF
Service
Design**

Outline

1. **Motivation—Network Centric Warfare**
2. **The Foundation of Information-Sharing: The GIG**
 - **Service-Oriented Architectures**
3. **Communities of Interest**
4. **Information Reqmts for a COI: Mission Capability Packages**
5. **The Nature of Advanced C2 Structures in NCW**
6. **Implications for Research in DF and C2 COI's in NCW**

1. Motivation—Network Centric Warfare

Tenets and Assertions of Network-Centric Warfare*

- A **robustly networked force** improves information sharing
- **Information sharing** enhances the quality of information and shared situational awareness.
- **Shared situational awareness** enables collaboration and self-synchronization, and enhances sustainability and speed of command.
- **ie enable New Paradigms of C2**
- These, in turn, **dramatically increase mission effectiveness, primarily thru agility and speed of action**

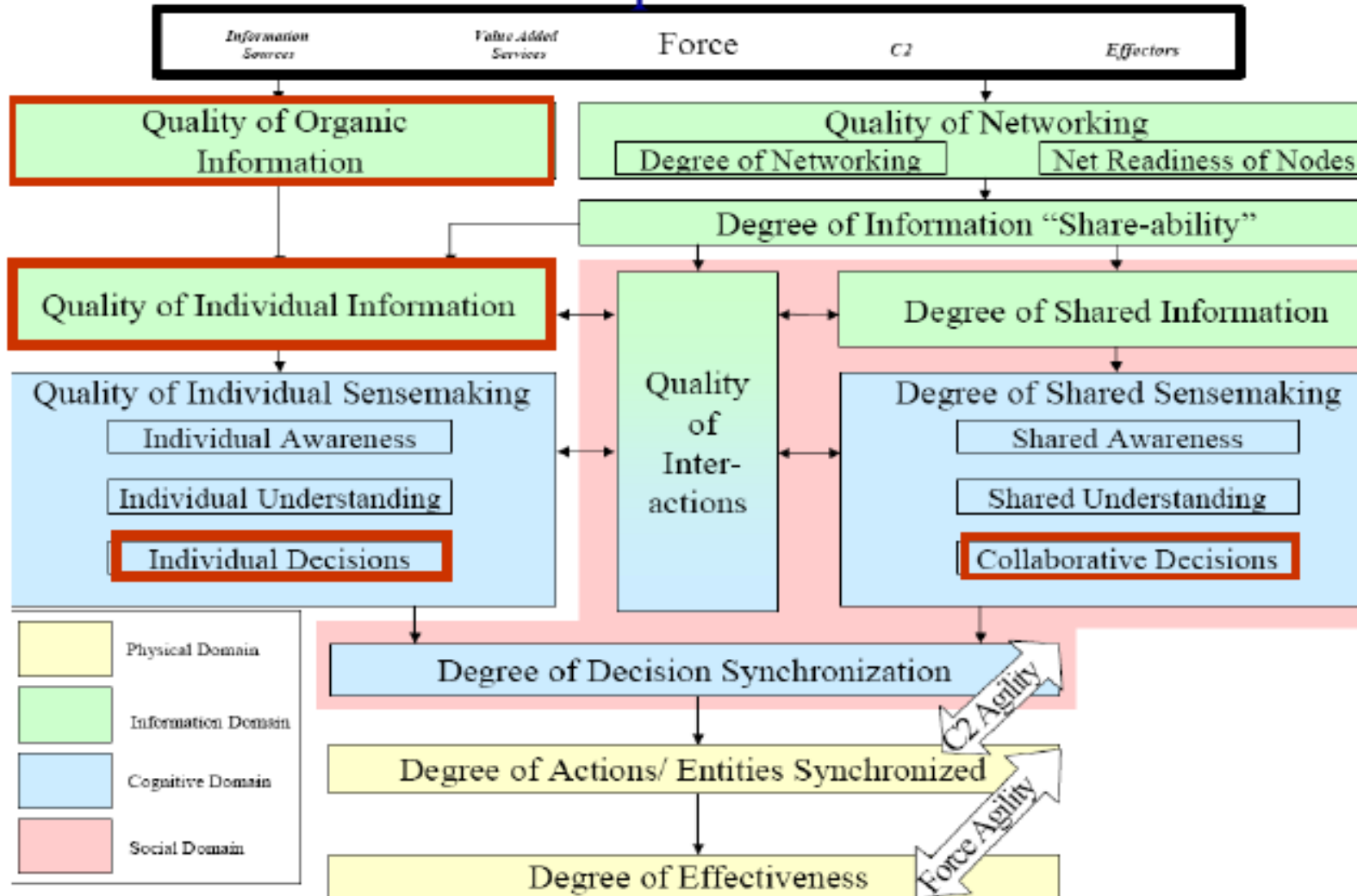
* See e.g., “Power to the Edge”, Alberts and Hayes, http://www.dodccrp.org/publications/pdf/Alberts_Power.pdf

Why NCW?

- Today's defense and security problems involve:
 - Selective search over large sets of possibilities
 - Complex ill-defined goals
 - Nature of problem changes as it is explored
 - Computational complexity
 - Analogies
 - Metaphors
 - Uncertainty: deterministic and stochastic
- Requires agile, rapid C2
 - Inconsistent with "Industrial Age" C2
 - New C2 operational paradigms

Network-Centric Operations*

NCO Conceptual Framework



* See Col Gary Agron, Col Chuck Pattillo, Network Centric Operations: The Power of Information Age Concepts and Technologies, http://www.oft.osd.mil/library/library_files/briefing_382_Agron_Patio_Presentation_v4.pdf.

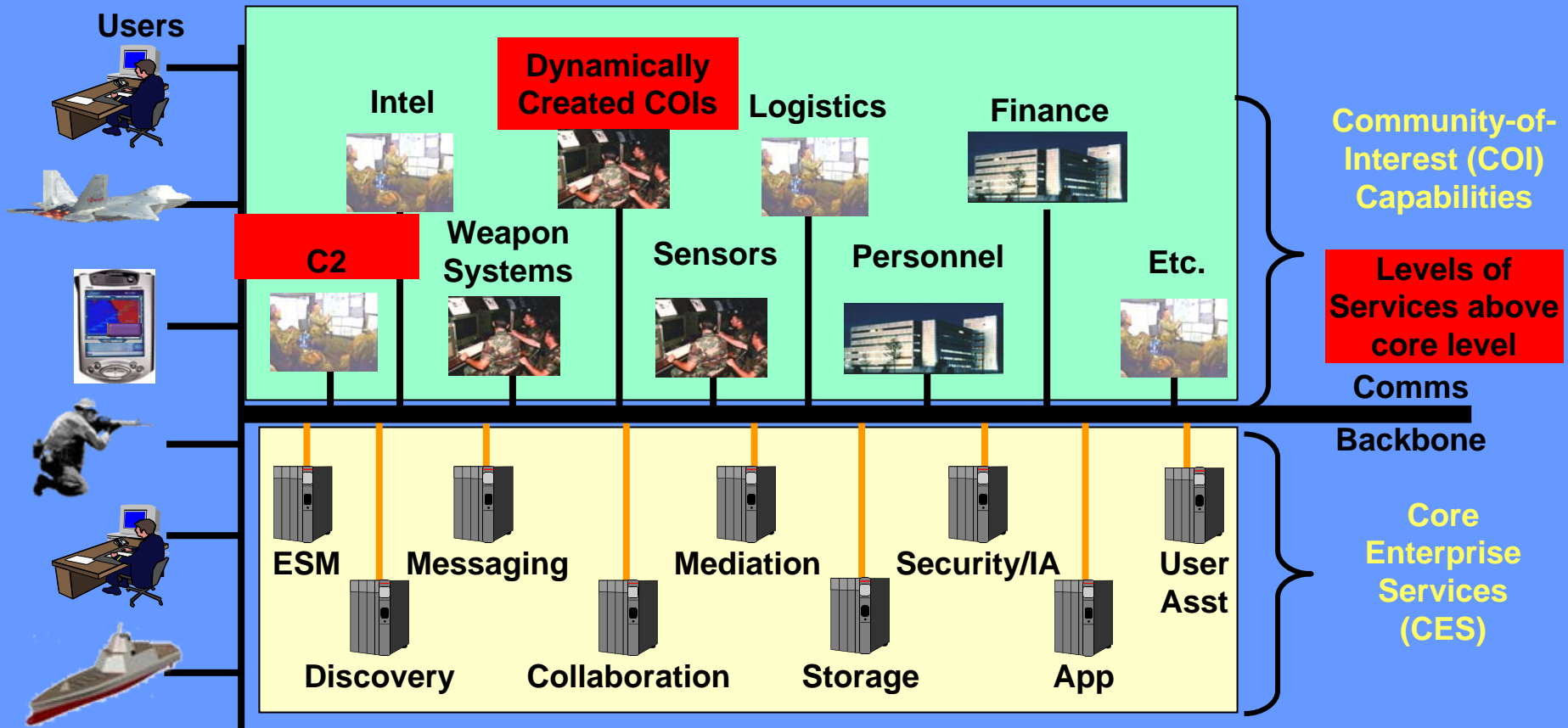
Impacts of NCW/NEC on DF and C2ISR

- These ideas introduce various critical notions affecting both DF and C2ISR:
 - Strategy by which information is shared
 - “Sensemaking”-Individual and Collaborative
 - Quality and Degree of:
 - Shared information
 - Individual sensemaking and decision-making
 - Interactions
 - Nature of “Self-Synchronization” of decisions and actions
 - Agility in C2

**What is the impact on DF/C2 Research Methodology
and DF Service design ?**

2. The Foundation of Information-Sharing: The “Global Information Grid (GIG)”

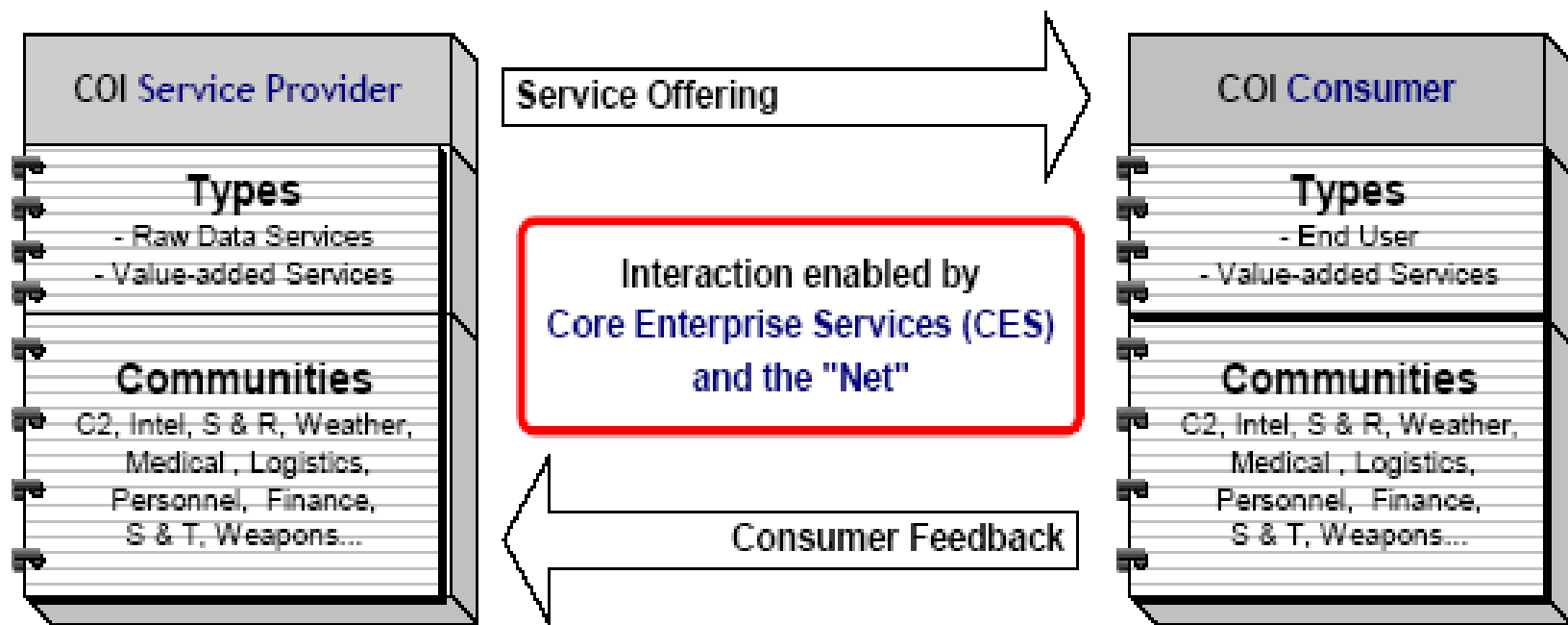
GIG: Net-Centric Enterprise Services (NCES)



A "Service-Oriented Architecture (SOA)" aka
"Service-Based Architecture (SBA)"

Nature of a Service Oriented Architecture

Service Provider-Consumer Relationships



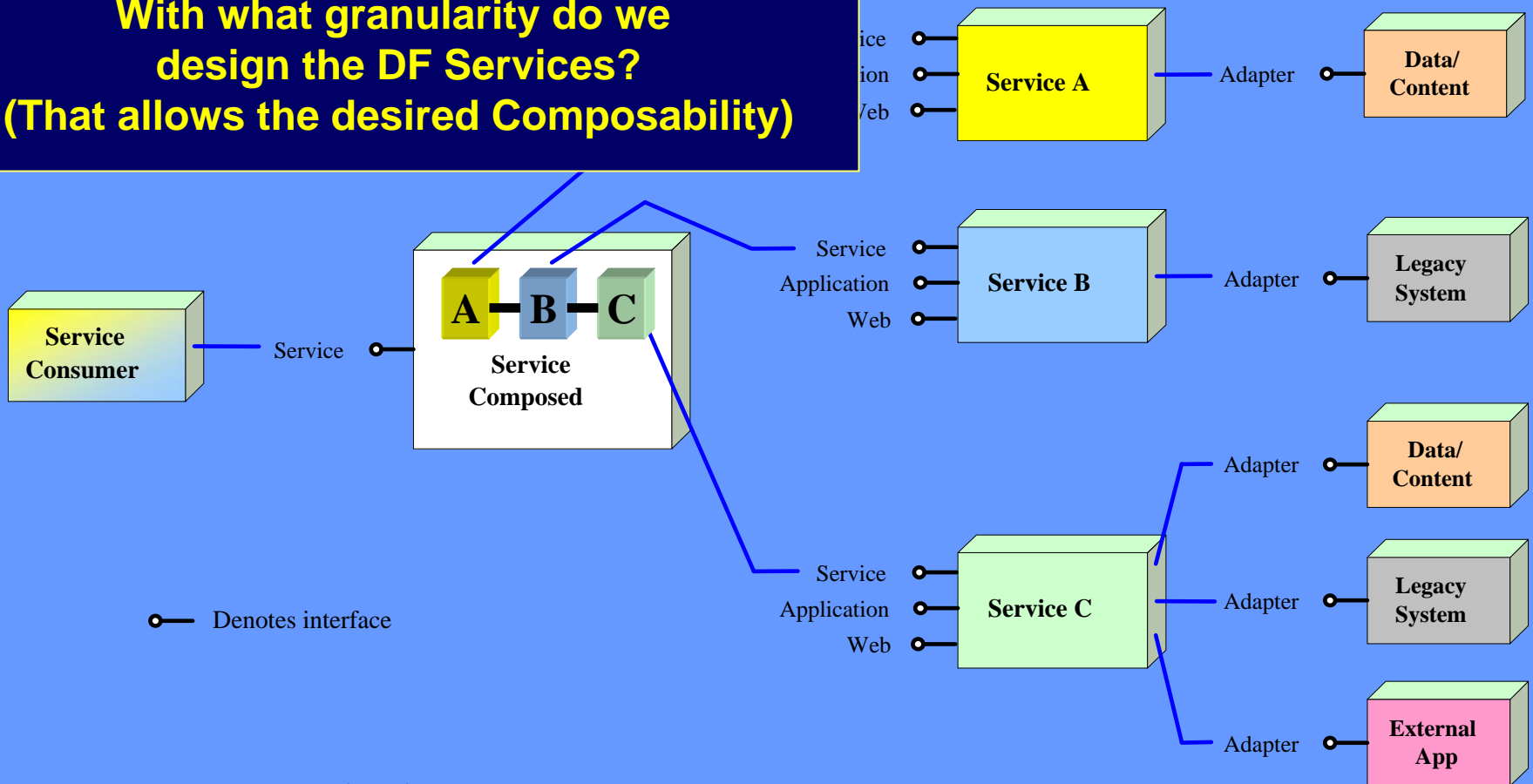
Agility : Composable Services

**Higher-Level Service Composed of Lower-Level
“Fundamental” or “Atomic” Services**

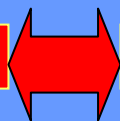
Higher-Level Service

Lower-Level Services
(statically created)

**Generates a Design Question:
With what granularity do we
design the DF Services?
(That allows the desired Composability)**



C2 COI Consumer



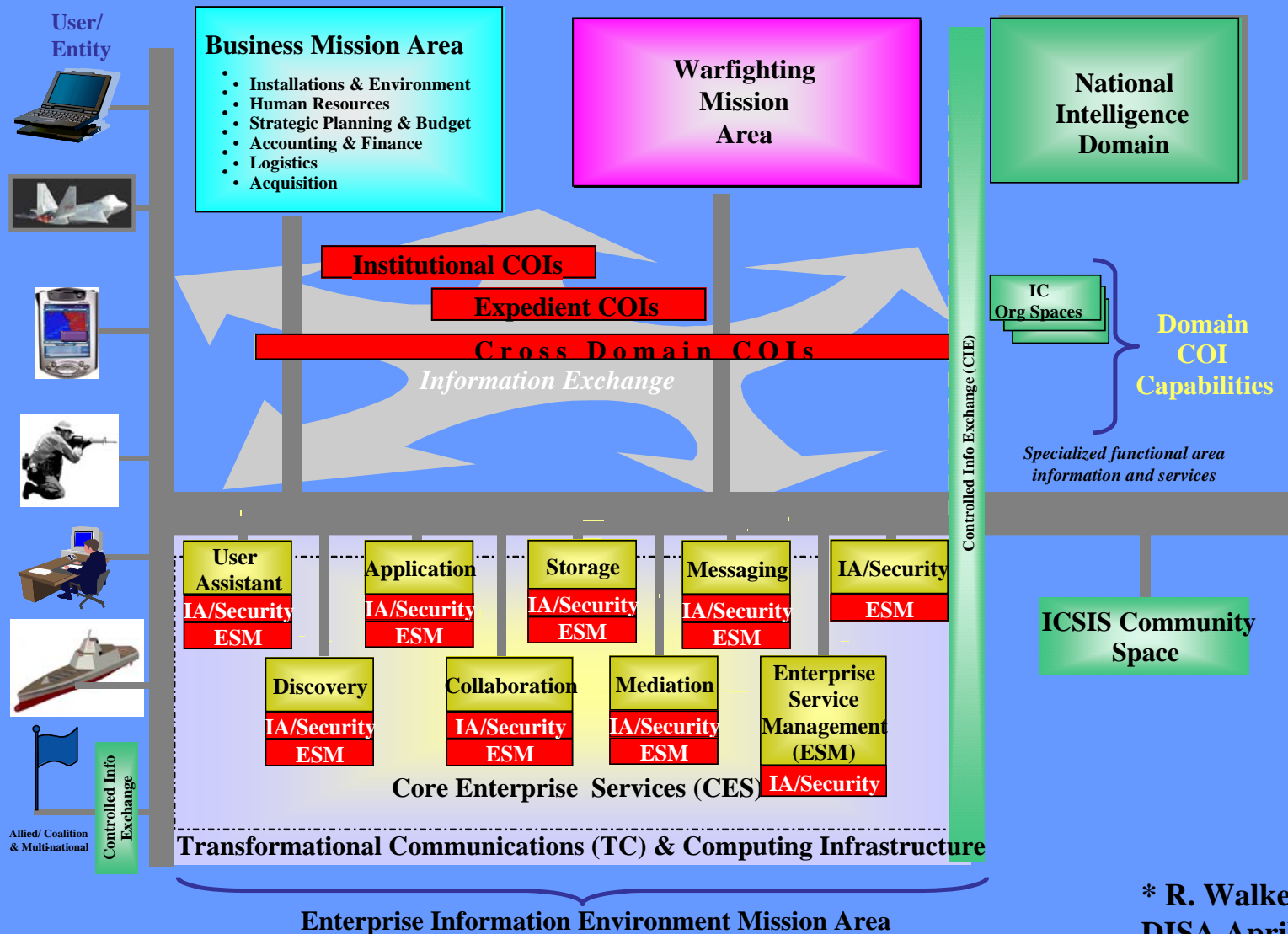
DF Service

(Some) Influences on Fusion Service Design in a Service-based Architecture

- Intermittent Network Connectivity and Dynamic Network Topology (the Core Services are not guaranteed 24 x 7)
- Only selected services will have deterministic response times and scheduling
- Challenge of maintaining data integrity and consistency—this is essentially a Distributed DF environment
- Strategy for employment of core comms infrastructure services
 - Point to Point (P2P)
 - Publish/Subscribe (P/S)
 - Client/Server (C/S)
 - Groups
- Security management (what Service-Consumer connections are allowed, under what security circumstances?)
- Other, TBD
- In sum, Reqmts for Managing Contingencies

3. Communities of Interest

The User Side of the GIG : “Communities of Interest” *



* R. Walker Brfg
DISA April 2004

COI's

- **Communities of Interest (COIs)** is the inclusive term used to describe **collaborative groups of users** who must exchange information in pursuit of their shared goals, interests, missions, or business processes and who therefore must have shared vocabulary for the information they exchange.

From COI FAQ's *

- “Q9: What are the criteria for qualifying as a COI?”
- There are no specific criteria for ‘qualifying’ as a COI. Any group of users who must exchange information may be a COI. Also, there is no “special process” for designating or establishing a COI. The Net-Centric Data Strategy encourages COIs to take the initiative in providing the organization and maintenance construct. “
- How will the C2 COI establish a set of COI's?
- What will their information requirements be?

* Communities of Interest in the Net-Centric DoD Frequently Asked Questions (FAQ),
http://www.defenselink.mil/nii/org/cio/doc/COI_FAQ.doc

Dynamics and Emergence of COI's

- One point to keep in mind here is that the **COI concept simply reflects a market-driven type idea**, in that SP's and SC's **will somehow evolve** to identify themselves to each other, either in an a priori way or in a dynamic, discovery-based way, **so that any SP has the task of identifying potential SC's and also other SP's necessary to their own function as Service Provider.**
- In other words, **the SP—eg a Data Fusion SP-- has a requirement to identify the “service network” in which it is planning to operate, ie the COI's that it will provide service to**

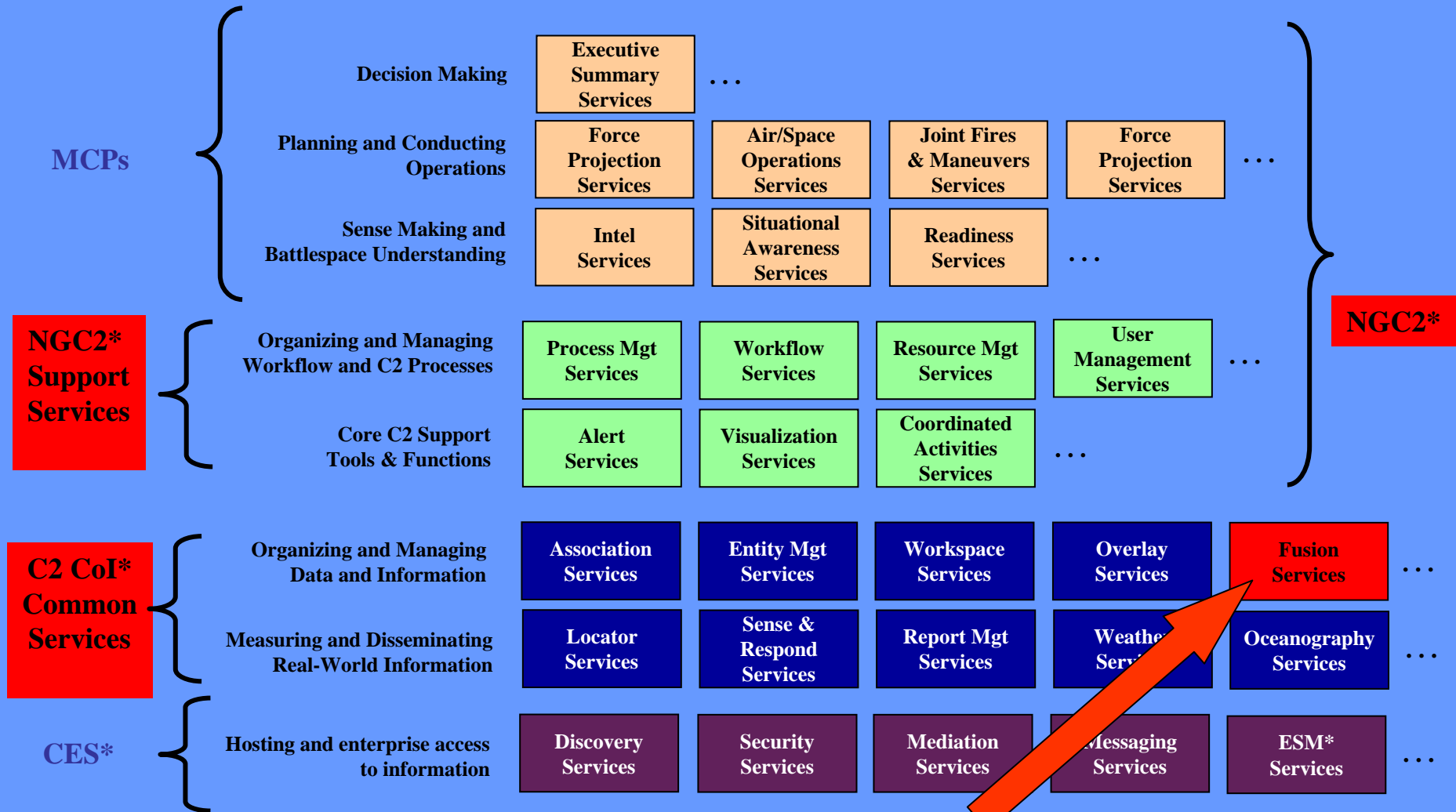
Imputes a requirement to understand the nature of C2 COI dynamics—what they are doing and what DF-based information they need to do it

(see later on Complex Adaptive Systems)

More on COI's: 4 Types are defined

Expedient	<p>Tactically driven, Implied authority, Formal processes modified for need, Relatively many entities (e.g., New Imagery Analysis capability for Damage Assessment)</p>	<p>Tactically driven, Derived authority, Ad hoc processes, Many entities (e.g., Forward deployed JTF planning New Threat Response)</p>
	<p>Explicitly recognized, Longer term, More formalized processes based on span of control, Relatively few entities (e.g., PSAs such as Logistics)</p>	<p>Explicitly or implicitly recognized, Longer term but priority driven, Blended processes resulting from agreements (e.g., JS area such as Battlespace Awareness)</p>
Institutional	Functional	Cross-Functional

Layered Services in Support of Warfighting Functions



* MCP – Mission Capability Packages
 NGC2 – Next Generation Command and Control
 COI – Community of Interest
 CES – Core Enterprise Services
 ESM – Enterprise Service Management

NOTE : FUSION SERVICES as part of the C2 COI Common Services

4. Information Requirements for a COI: Mission Capability Packages

What Information Does Such a COI Require?

- Given this, a question is: **“what service or product does the DFS provide to the C2 COI?”** According to the NCES-related architecture, the informational requirements within C2 should be those requirements for Joint C2; these requirements are spelled out in the **Joint C2 Operational Requirements Document** or JC2 ORD and are derived in accordance with several

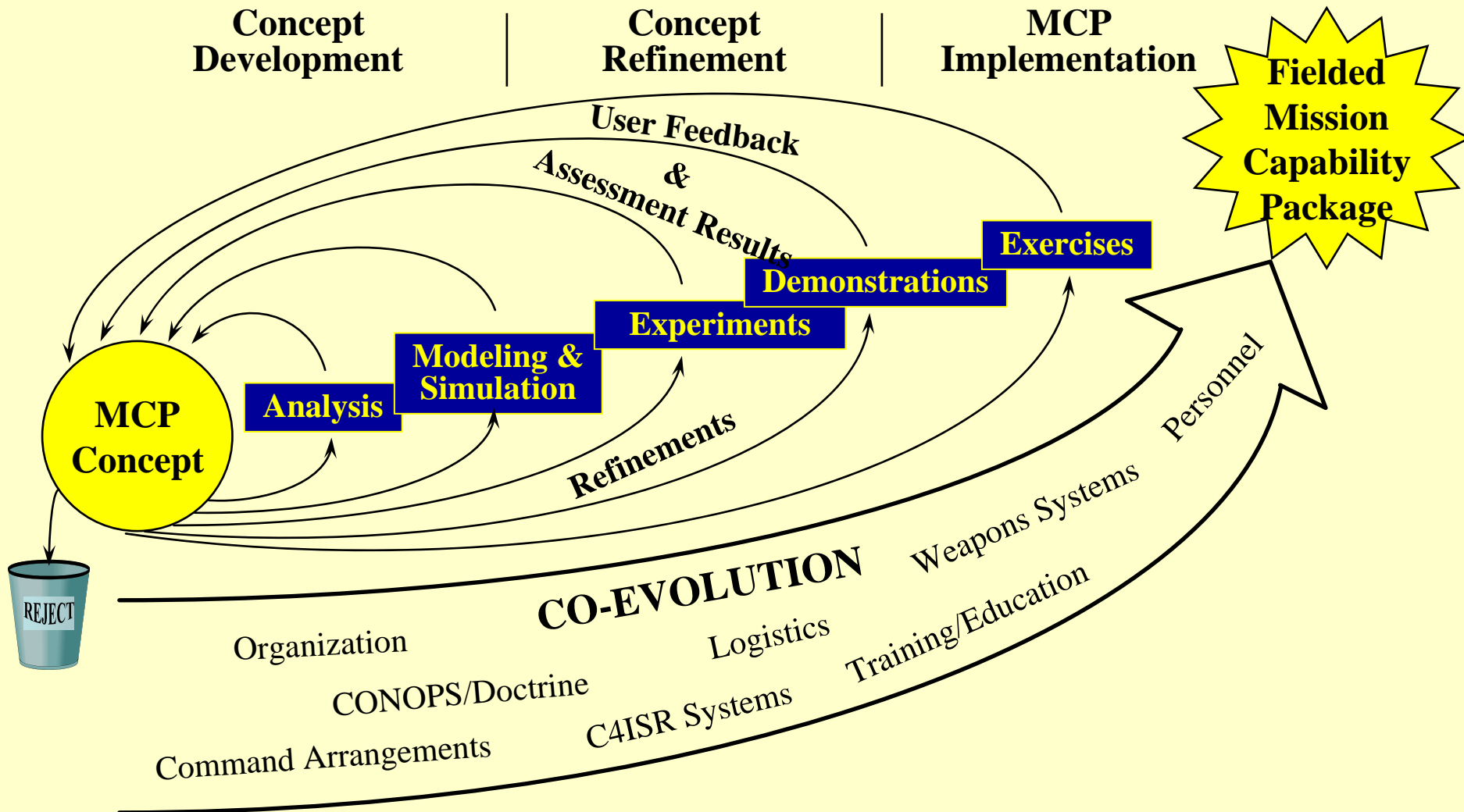
“Mission Capability Packages (MCP)”.

Recall yesterday: ACT working on MCP's

Mission Capability Packages*

- A JMCP is a capabilities-based force package composed of fielded weapon systems possessing interoperable information network equipment.
- The desired characteristics of a JMCP depend upon the tasks which prompt its formation, but all JMCPs will have common requirements, which can be derived from the NCW Value Chain
- So this can be done for a set of expected Missions and Tasks—but not for atypical, unexpected adversarial behaviors

The Creation of a Mission Capability Package*



5. The Nature of Advanced C2 Structures in NCW

Control of Combat

- Combat is complex—but some types more than others
- The “Law of Requisite Variety” *, argues that to properly control such a system, the variety of the controller function (the number of accessible states which it can occupy) must match the variety of the combat system itself. In other words, the control system itself, here the C2 organization, has to be complex, with great agility, at least for the “tough problems”
- Argues for **any NCW C2 COI** as a
 - **“Complex Adaptive System (CAS)”**

Land Combat as a Complex Adaptive System *

General Property of Complex Systems	Description of Relevance to Land Warfare
<i>Nonlinear interaction</i>	Combat forces composed of a large number of nonlinearly interacting parts; sources include feedback loops in C2 hierarchy, interpretation of (and adaptation to) enemy actions, decision-making process, and elements of chance
<i>Nonreductionist</i>	The fighting ability of a combat force cannot be understood as a simple aggregate function of the fighting ability of individual combatants
<i>Emergent Behavior</i>	The global patterns of behavior on the combat battlefield unfold, or emerge, out of nested sequences of local interaction rules and doctrine
<i>Hierarchical structure</i>	Combat forces are typically organized in a command and control (fractal-like) hierarchy
<i>Decentralized control</i>	There is no master "oracle" dictating the actions of each and every combatant; the course of a battle is ultimately dictated by local decisions made by each combatant
<i>Self-organization</i>	Local action, which often appears "chaotic," induces long-range order
<i>Nonequilibrium order</i>	Military conflicts, by their nature, proceed far from equilibrium; understanding how combat unfolds is more important than knowing the "end state"
<i>Adaptation</i>	In order to survive, combat forces must continually adapt to a changing environment, and continually look for better ways of adapting to the adaptation pattern of their enemy
<i>Collectivist dynamics</i>	There is a continual feedback between the behavior of (low-level) combatants and the (high-level) command structure

Table 1: Land combat as a complex adaptive system.

Relations between Complexity Factors and Force Factors *

COMPLEXITY CONCEPT	INFORMATION AGE FORCE
<i>Nonlinear interaction</i>	Combat forces composed of a large number of nonlinearly interacting parts.
<i>Decentralised Control</i>	There is no master “oracle” dictating the actions of each and every combatant.
<i>Self-Organization</i>	Local action, which often appears “chaotic,” induces long-range order.
<i>Nonequilibrium Order</i>	Military conflicts, by their nature, proceed far from equilibrium. Correlation of local effects is key.
<i>Adaptation</i>	Combat forces must continually adapt and coevolve in a changing environment.
<i>Collectivist Dynamics</i>	There is a continual feedback between the behaviour of combatants and the command structure.

* James Moffat, “Complexity Theory and Network Centric Warfare”, CCRP Press, 2003

Properties of Complex Adaptive Systems*

1. **Aggregation:** both in structure and in macro-functionality (which governs emergent macro-behavior)
2. **Nonlinearity:** The behavior of CAS's is not linear, and their interactions are thus not simply additive.
3. **Flows:** concern how information, stimuli, resources among agents propagate and vary over time
4. **Diversity:** relates to ability to aggregate the overall environmental state (eg from diverse points of view)—a “multiple hypothesis” notion

* J.H.Holland, “Hidden Order: How Adaptation Builds Complexity”, Reading: Addison- Wesley, also “Emergence: from Chaos to Order”

Mechanisms of Complex Adaptive Systems*

1. **Tagging:** Agents in a CAS are able to recognize and differentiate among one another via “labelled interactions” –basis for sharing, filtering, aggregating, etc—a sort of “Pedigree” tag
2. **Internal Models:** provide the basis for anticipation and prediction—ie foreknowledge—two types: tacit for current actions and overt that allows look-ahead
3. **Building Blocks:** structural parts of the internal models

* J.H.Holland, “Hidden Order: How Adaptation Builds Complexity”, Reading: Addison- Wesley, also “Emergence: from Chaos to Order”

Relations Between C2 and CAS *

Command and Control Framework Subjects	Complex Adaptive System Micro-Characteristics
Organization	Numbers and types of agents Patterns and structure of agents connections Types/density of interactions (Macro-level self organization)
Operations	Rule-based behavior Fitness judgment (combat)
Command	No macro-level parallel Rule application
Leadership	Organization design and micro-characteristics
Doctrine	Agent rules Experience preservation, anticipation Common language for interaction (tags)
Training	Competition and fitness judgment Applied rule generation Successful rule dissemination
Education	Theoretical rule generation Successful rule dissemination
Systems	Coordination infrastructure Connection density, bandwidth Frequency of interaction

This List provides Guidance on the choice of “Factors” to use in Expts Studying C2 as CAS’s

* David K. Gerber, “Adaptive Command and Control of Theater Airpower”, USAF Thesis School of Advanced Airpower Studies, Air University Press, Maxwell Air Force Base, Alabama, March 1999

Engineering Principles for CAS*

- **Agent Things, not Functions** —components of the CAS should not result from a fctl decomposition but represent physical entities in the world of interest— eg people, platforms
- **Keep Agents Small** —
 - *Small in “size”*--in part aids in realizing benefits of combinatorial (aggregate) behaviors—eg the number of behaviors that N agents, each having M local behaviors, can perform is N^M
 - *Small in Time (Forgetful)* —done well leads to removal of errors in hypotheses
 - *Small in Scope (Local Sensing and Action)* —also bounded intercommunications--done well allows beneficial focusing
- **Decentralize System Control** —avoids single point of failure, bottlenecks, etc
- **Support Agent Diversity** —notion of diversity is case-specific

* “Go to the Ant”: Engineering Principles from Natural Multi-Agent Systems, H. Van Dyke Parunak, Annals of Operations Research, special issue on Artificial Intelligence and Management Science.

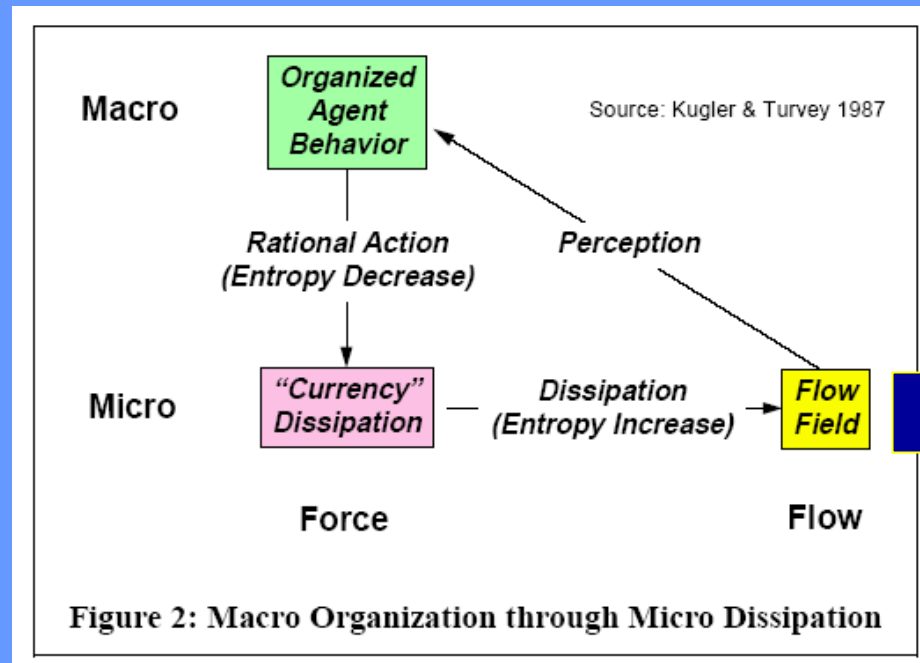
Engineering Principles for CAS - cont'd

- Provide an Entropy Leak* --

“Good Macro-Behavior”

Tension

“Persistent Disequilibrium”



ie, The CAS as an “Open System” that dissipates more entropy with the environment than (1) they produce internally (Micro level) and (2) than they import from the environment

* Second Law of Thermodynamics observes that closed systems progressively become more disordered over time.

Engineering Principles for CAS - cont'd

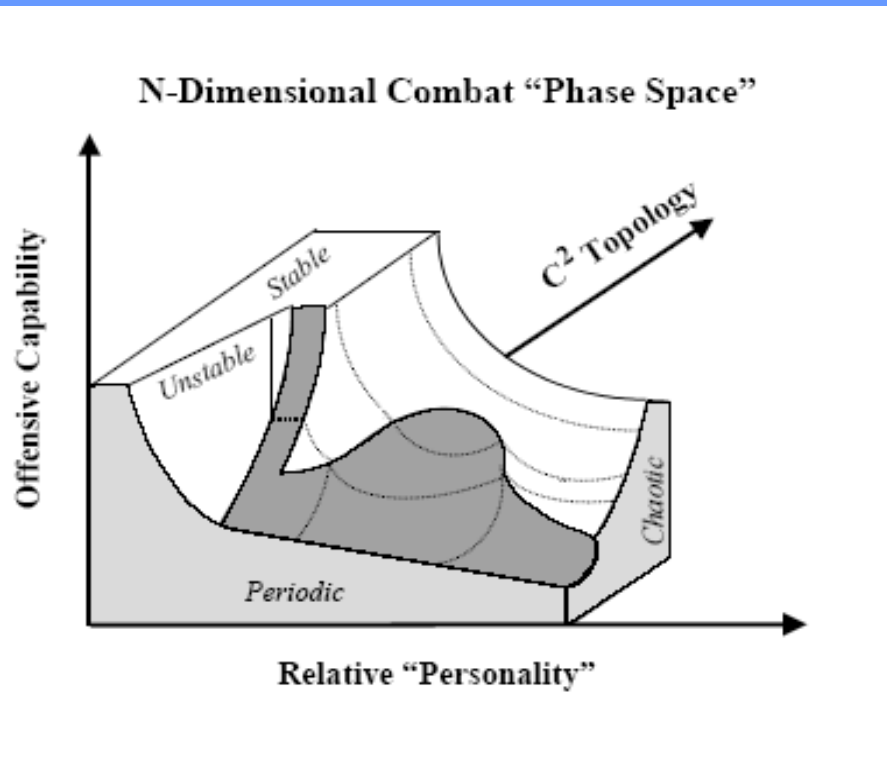
- **Enable Agents to Share Information**
- **Plan and Execute Concurrently** —“pursue no optima” (if environment very dynamic, no steady state to target)—coherence by dynamics of interaction, not planning

Controlling Complex Systems*

- Elements of Self-Organization:
 - Interacting components
 - C2 agents in the COI
 - Constructive processes
 - Consensus formation
 - Destructive processes
 - Adjudication, deletion of conflicting elements
 - Positive and negative feedback
 - Shared understanding without runaway views
 - Nonlinearity
 - Positive magnification and squelching

Operating “On the Edge of Chaos”

(1)



(2)

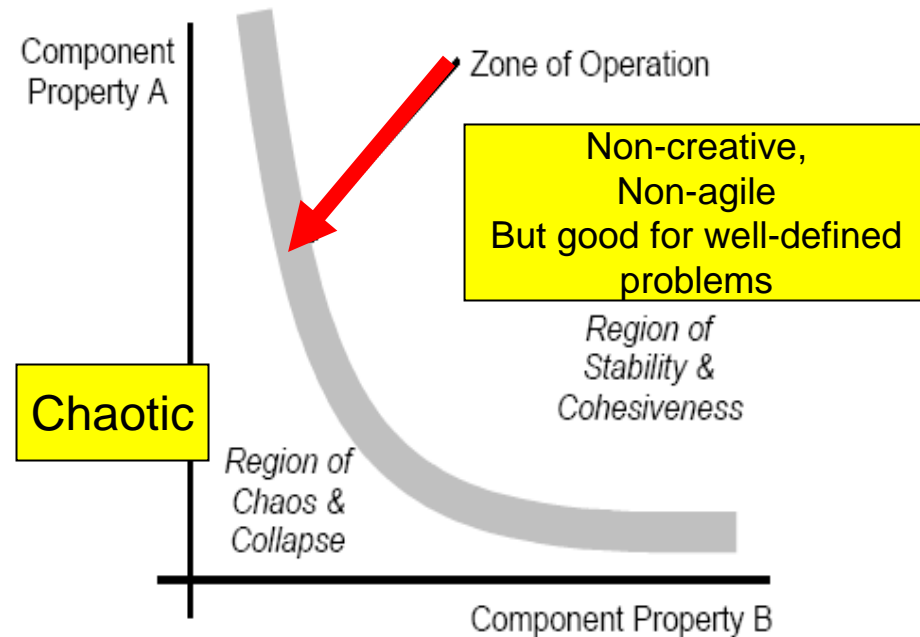


Figure 6. Zone of Operation in a Complex Adaptive System

(1) A. Ilachinski, "An Artificial-Life Approach to War", Ctr for Naval Analyses brfg, <http://www.cna.org.isaac/>.

(2) Final report, Sensemaking Symposium, CCRP pgm, Oct 2001

Motivation to Study CAS's*

- “So why study complex systems or emergent behavior?”
- **The prime research objective is to understand complex adaptive systems well enough to predict their macro-level behavior.**
- A related goal is to design and construct a complex adaptive system with a desired, or perhaps bounded, emergent behavior with a theoretical understanding that the emergent behavior will be most fit for a particular objective.
 - **Unfortunately, the science has not found an answer to either of these problems.”**

Research Activities on NCW and CAS

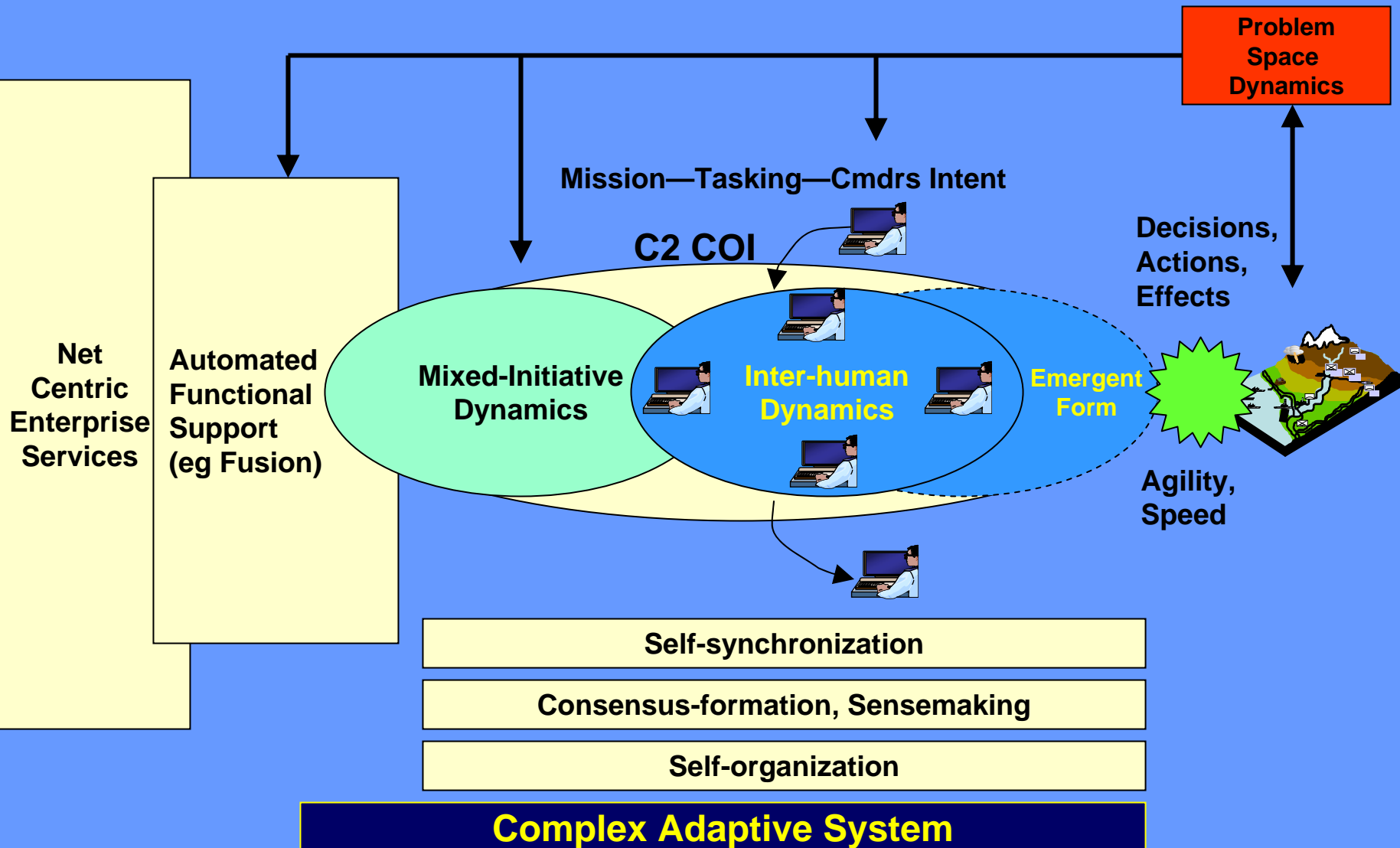
- **US Joint Forces Command**
 - Millennium Challenge Expts
 - Multinational Experiments incl NATO
- **US Marine Corps: “Project Albert”**
 - <http://www.projectalbert.org/>
- **US Center for Naval Analyses:** Projects “ISAAC” and “EINSTEIN”
 - <http://www.cna.org/isaac/on-line-papers.htm>
- **US Army**
 - Joint Virtual Battlespace Sim
 - Army Transformational Wargame Sim
- **US Air Force**
 - Various funded works, eg Univ Cincinnati CAS Lab
- See papers from **US CCRP program** conferences, also MORS

However.....engineered complex systems are also, to varying degrees:

- Unpredictable.
- Open-ended.
- Opaque.
- Imperfect.
- Imprecise.
- Uncertain.

Can we live with this?

Dynamics in Network-Centric Warfare



6. Implications for Research on DF and CAS in NCW

- Research Frameworks**
- Testing and Evaluation**

One Further Motivation (Roske)

(Back to the “Entropy Leak”)

“Why has the analysis of C2ISR been so unsatisfying?

The reason may be that energy, in the form of ideas, initiative and imagination, expressed as perception and intent, are flowing across the boundary of the technical systems we define and have been trying to analyze. The result is that we do not control the cause-and-effect relationships in those “systems” because **the systems are open**; the responses are basically unbounded and unpredictable.

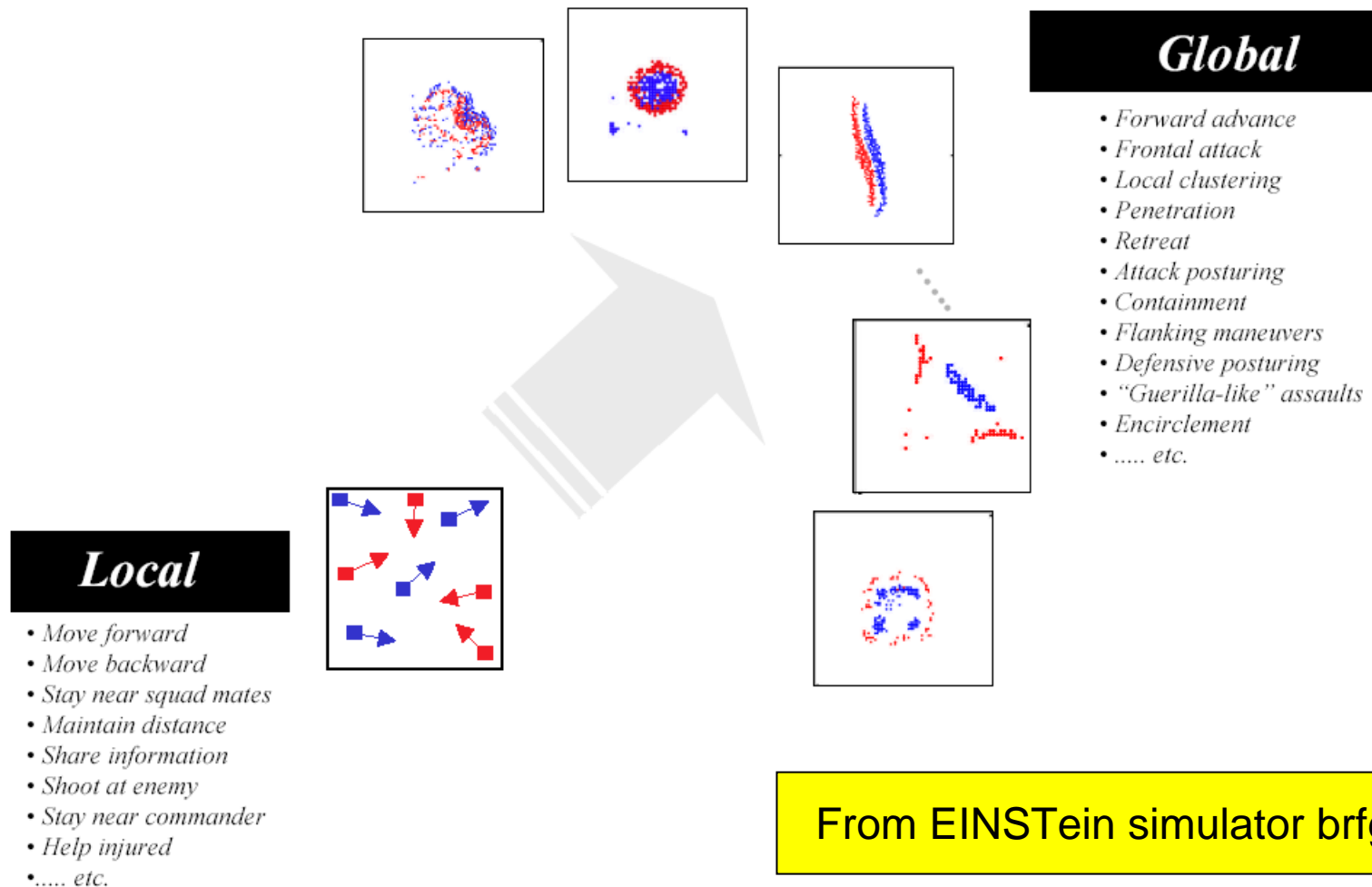
Perhaps we have been applying closed system analysis methodology to what is actually an open system problem. The presence of the human being introduces energy across the systems boundary and produces emergent and adaptive behaviors from the system. This is characteristic of open systems, particularly of complex adaptive systems. This is the language of open systems analysis.

It's no wonder that we haven't been very successful assessing what a pound of C2ISR is worth.”

Vincent P. Roske, Jr,
Deputy Director, J8 (Wargaming, Simulation & Analysis),
The Joint Staff

Research Frameworks

• Agent-based Testbeds



Research Frameworks

- **Hybrid Human-Agent Testbeds**
 - Exploits available agent-modeling SW
 - Allows realistic human participation
 - Focal studies on explicit Human Factors aspects
 - Perceptual, Cognitive reality
 - Arguably are Open Systems

Challenges to Experimental Design *

Table 1: The Experimental Environment

Traditional DOE Assumptions	Agent-based Model Characteristics
Small or moderate number of factors	Large number of factors
Linear or low-order effects	Non-linear, non-polynomial behavior
Sparse effects	Many substantial effects
Negligible higher-order interactions	Substantial higher-order interactions
Homogeneous errors	Heterogeneous errors
Normally distributed errors	Various error distributions
Black box model	Substantial expertise exists
Univariate response	Many performance measures of interest

* S. Sanchez and T. Lucas, "EXPLORING THE WORLD OF AGENT-BASED SIMULATIONS: SIMPLE MODELS, COMPLEX ANALYSES", Proceedings of the 2002 Winter Simulation Conference

Considerations in Experimental Design for Simulation-based DF/C2 Research*

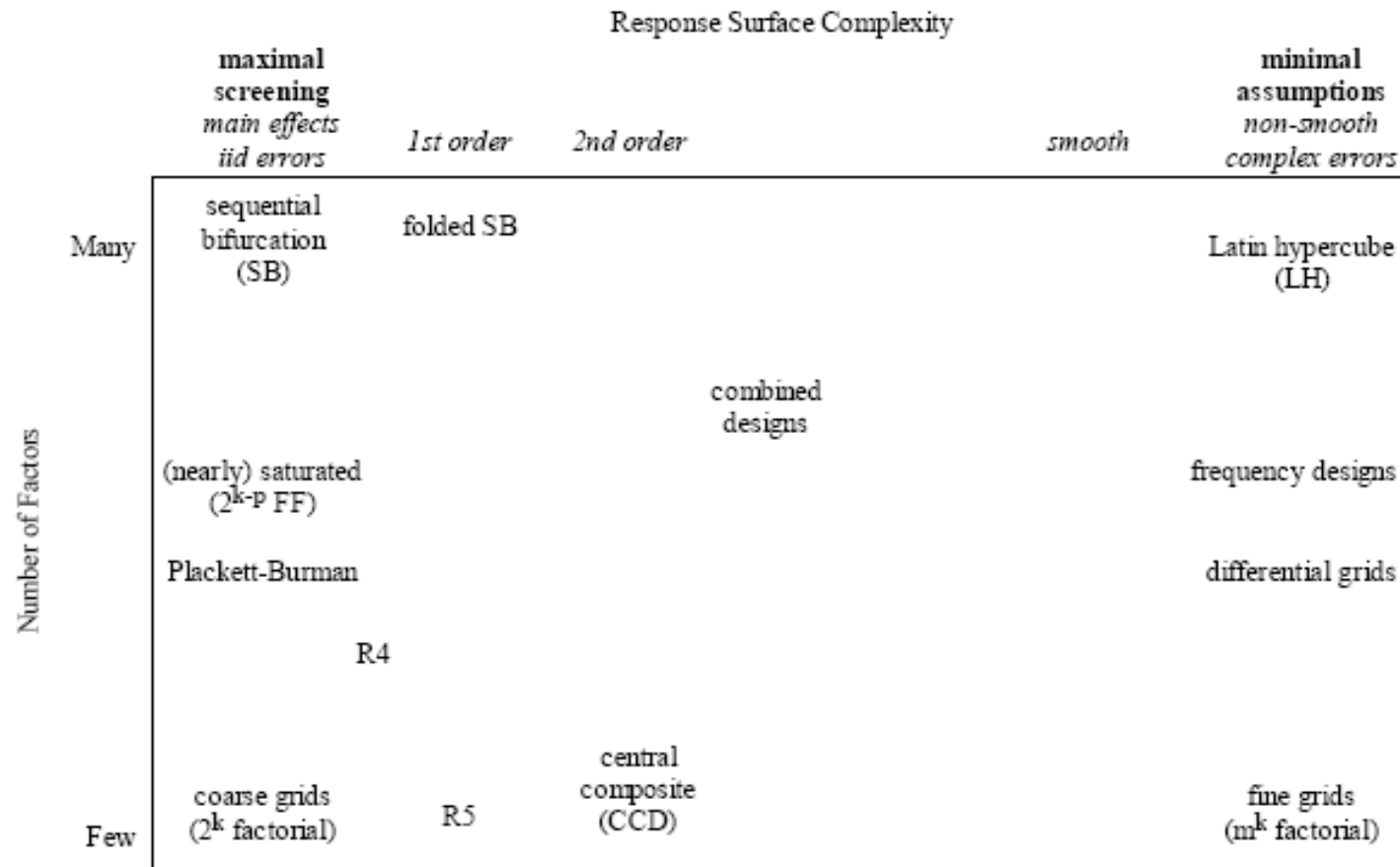


Figure 1: Recommended Designs According to the Number of Factors and System Complexity Assumptions

* See J. P.C. Kleijnen et al, "A User's Guide to the Brave New World of Designing Simulation Experiments", INFORMS Journal on Computing , 2003

Summarizing Effects on DF Design

- **NCW and SOA-Driven:**

- Concern for Quality of DF Service, Products as delivered in an SOA environment
- Large hypothesis spaces:
 - Adversary models: deductive / abductive
 - Normality models
 - Inductive-new model discovery
 - Accounting for Negative Information
- Temporally agile—“pursue no optima”
- Linked to collaborative/sharing/consensus-building interactions
- Able to manage contingencies imputed by NCES
- Support “intimate” Mixed-Initiative processes
- Evaluation based on formal/DOE T&E methods

Summarizing Effects on DF Design

- **CAS-Driven:**

- **Re Properties:**

- Support C2 COI design of amplification/squelching techniques to control non-linear effects
 - Supporting C2 COI's of high diversity

- **Re Mechanisms:**

- Incorporate DF Pedigree in Agent Tags Schema
 - Architectural fit to Agent Internal Models and Bldg Blocks

- **Re CAS Design Principles:**

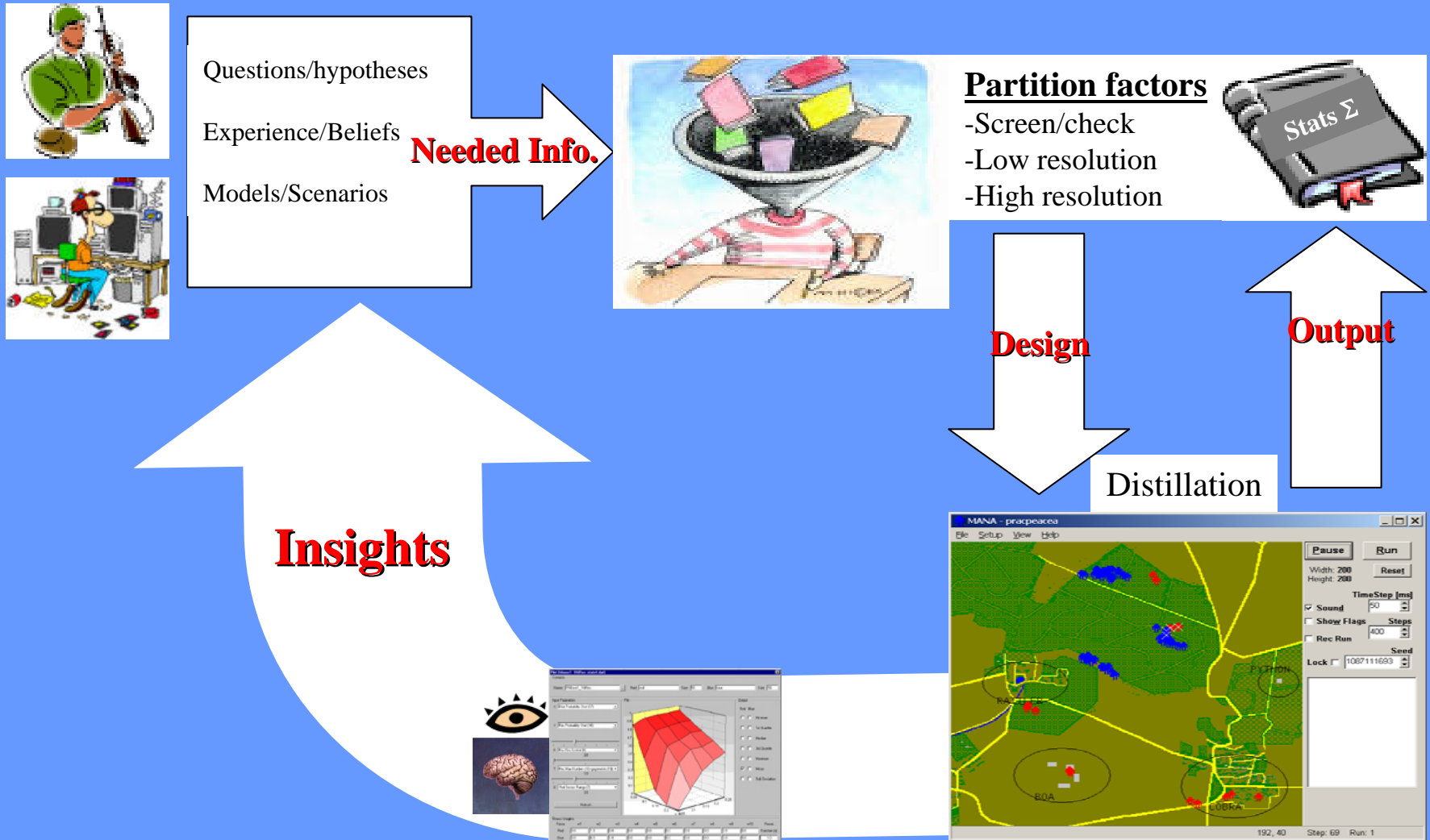
- “good” fading memory of DF processes
 - Support / fit to Macro-Micro rules for “good” entropy exchange

Summary

- New Research Initiatives and Paradigms are needed to explore these notional impacts of NCW, SOA, and CAS on DF process/service design
- Requires an R&D collaboration among the CAS/Agent, Human Engineering, and the DF communities
- **Technology Roadmap-type thinking** needs to begin to initiate and plan this R&D process in a cost-effective way.

backups

Putting together an automatic design process*



* S. Sanchez and T. Lucas, "Getting the Most From Your Distillation: Efficient High-dimensional Explorations", 5th Project Albert International Workshop, July 2002

Summary

- Strategies and Methodologies for the Design of specific Services that will operate within the GIG/NCES infrastructure are still evolving
- As in the design of all Data Fusion processes, here too the key is understanding the C2 COI concepts and the specifics of the COI structure for any given application
 - ie Understanding the User's Informational Needs
- This requires deep analysis and understanding of the concepts and processes of Complex Adaptive Systems, Ubiquitous C2 and the realities of how such systems are engineered
- Developing the design knowledge regarding CAS's to yield predictable or bounded C2 behavior and "good" DF Service designs will require experimentation involving simulation of integrated NCW-type environments

Genesis of the GIG *

- **History**

- Motivated by Clinger-Cohen Act (Information Technology (IT) Management Reform Act of 1996), and tied into JV 2010, 2020
- It is intended to eventually provide the joint warfighter with a **single, end-to-end information system capability** that includes a secure network environment, allowing DoD users to access shared data and applications, regardless of location and supported by a robust network/information-centric infrastructure.

* See : (Clinger-Cohen): <http://irm.cit.nih.gov/itmra/> , (JV2010):<http://www.dtic.mil/jv2010/jvpub.htm>, (JV2020): <http://www.dtic.mil/jointvision/jvpub2.htm>

Self-Organizing Systems--defined

- “systems of many components that tend to reach a particular state, a set of cycling states, or a small volume of their state space, with no external interference”
- “an emergent structure that has integrated properties that are not inherent in the individual components”
- All the mechanisms dictating its behavior are internal to the system—no external control

More on Self-Organization

- See W. Ashby “the principle of self-organization”:
 - He noted that a dynamical system, independently of its type or composition, always tends to evolve towards a state of equilibrium, or what would now be called an *attractor*. This reduces the uncertainty we have about the system’s state, and therefore the system’s statistical entropy.
- Heinz von Foerster, formulated the principle of "order from noise".
 - He noted that, paradoxically, the larger the random perturbations ("noise") that affect a system, the more quickly it will self-organize (produce “order”). The idea is very simple: the more widely a system is made to move through its state space, the more quickly it will end up in an attractor.
- **Two features:**
 - Behaviors that tend to reduce uncertainty—entropy-reducing
 - Behaviors that explore wide ranges in possible task solutions—examine wide ranges of hypotheses

Sensemaking*

- Sensemaking is about such things as:
 - placement of items into frameworks,
 - comprehending,
 - redressing surprise,
 - constructing meaning,
 - interacting in pursuit of mutual understanding and patterning.
- It is not synonymous with interpretation or decision-making. It is not interpretation as it encompasses more than how cues, information is interpreted, but is concerned with how the cues were internalized in the first instance and how individuals decide to focus on specific cues

* Weick, K. (1995). *Sensemaking in Organizations*. Thousand Oaks Cal.: Sage Publications

See also Bavelas, J. B. (1973). Effects of the Temporal Context of Information. *Psychological Reports* 32(3) 98.

Sensemaking*

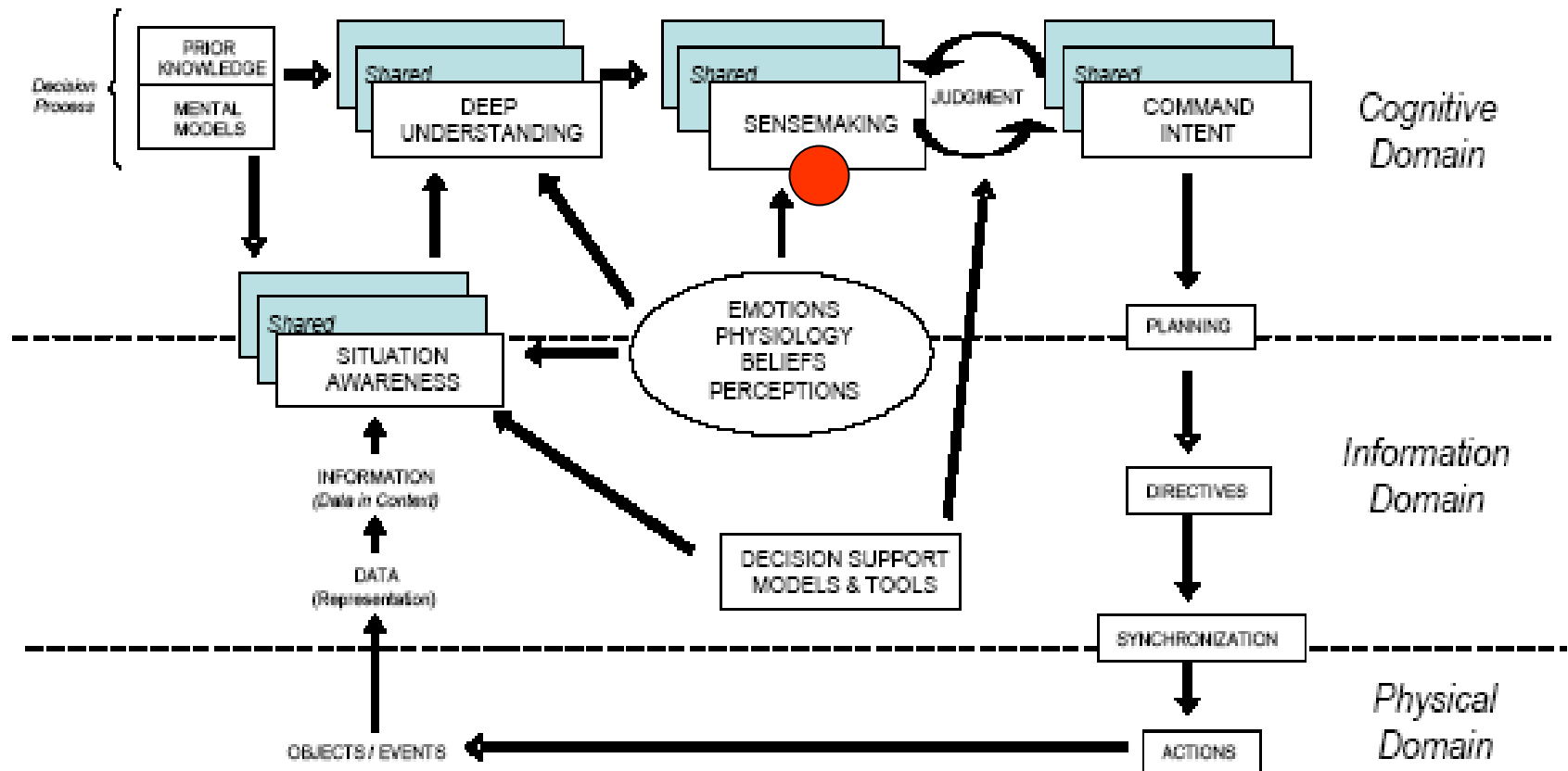


Figure 1. Sensemaking Conceptual Framework

Sensemaking*

- Within this research perspective, situation awareness is distinguished from knowledge and sensemaking in the following manner:
 - **Knowledge** is defined as the capacity for action (doing, saying, thinking).
 - **Situation awareness** is defined as dynamic “situated” knowledge, or the capacity to act effectively in a given specific situation.
 - **Sensemaking** is defined as the process of **creating situation awareness** in situations of uncertainty.

Self-synchronization-what is it?

- “Self-synchronization is a term that is specific to Network Centric Warfare. It is not found in complexity theory literature or in the literature discussing future Joint and Army warfighting concepts” (1).
- Synchronization is “the meaningful arrangement of things or effects in time and space.”
- Army doctrine (2) defines synchronization as “the arrangement of military actions in time, space, and purpose to produce maximum relative combat power at a decisive place and time.”
- A simple definition of self-synchronization is **“the ability of a well-informed force to organize and coordinate complex warfare from the bottom up.”**

1) Charles D. Costanza, Self-Synchronization, the Future Joint Force and the United States Army's Objective Force, School of Advanced Military Studies United States Army Command and General Staff College Fort Leavenworth, Kansas AY 02-03

2) U.S. Department of the Army, *Field Manual 101-5-1, Operational Terms and Graphics* Washington D.C.: Department of the Army, 1997)

Agility and Self-Synchronization

- NCW Desiderata: **Agility-or-autonomous teams working in concert**, continually adapting to changing conditions and environments.
- Complex adaptive systems (CAS) are characterized in terms of properties and mechanisms that when combined allow adaptation.
- Thus (?)—how do we move C2 paradigms to function as part of CAS's with desirable adaptive properties?
- That is, to manage combat such that combat has the adaptive properties of self-organized emergent phenomena?"

On Self-Synchronization*

- Among the characteristics identified as necessary for a future self-synchronizing force were trust, a common relevant operational picture, clear commander's intent, and empowered actors
 - Another aspect of trust is that DMs must trust the information in the network, especially the sources of information used to develop shared situation awareness.

Studies in Self-Synchronization

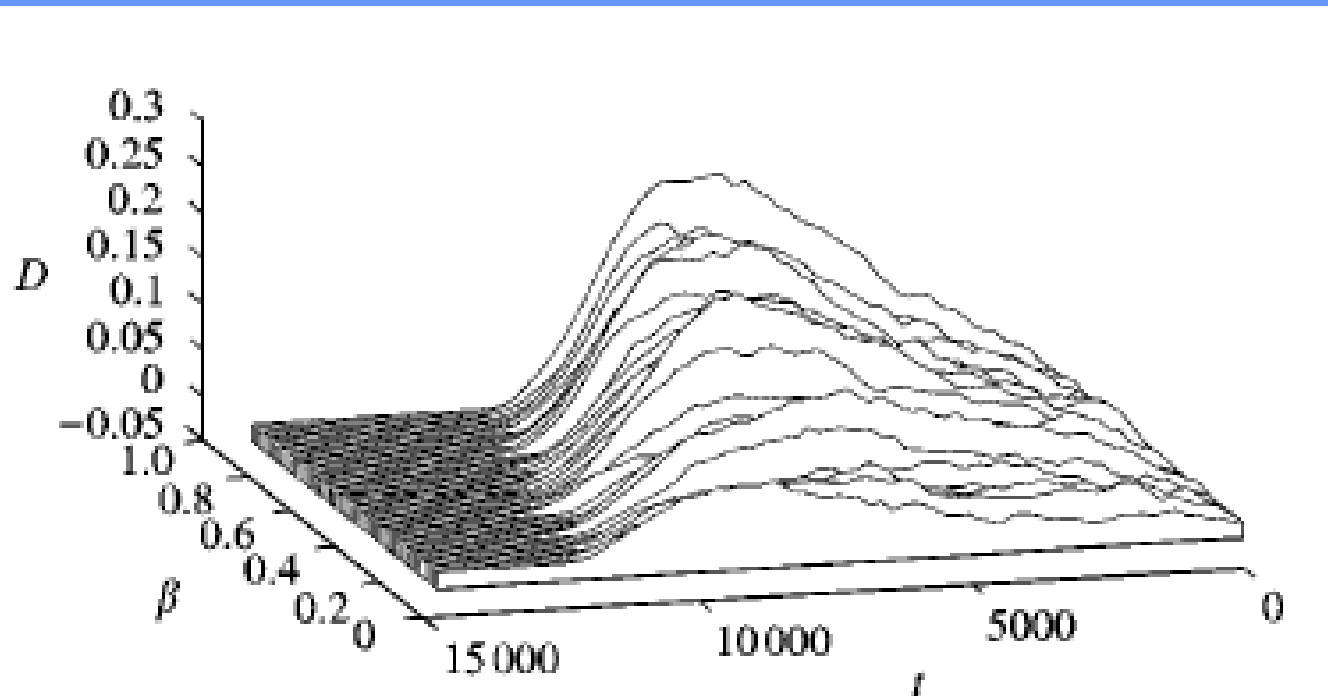


FIG. 7. $D(\beta, t)$ for $0 \leq \beta \leq 0.85$ and $C_{in} = 50\,000$. As hypothesized in the text, the maximum of $D(\beta, t)$, with β fixed, grows with β , showing clearly that the efficiency of self-synchronized behaviour strongly depends on the ability of individuals to stimulate each other.

Self-synchronization Within the OODA Loop

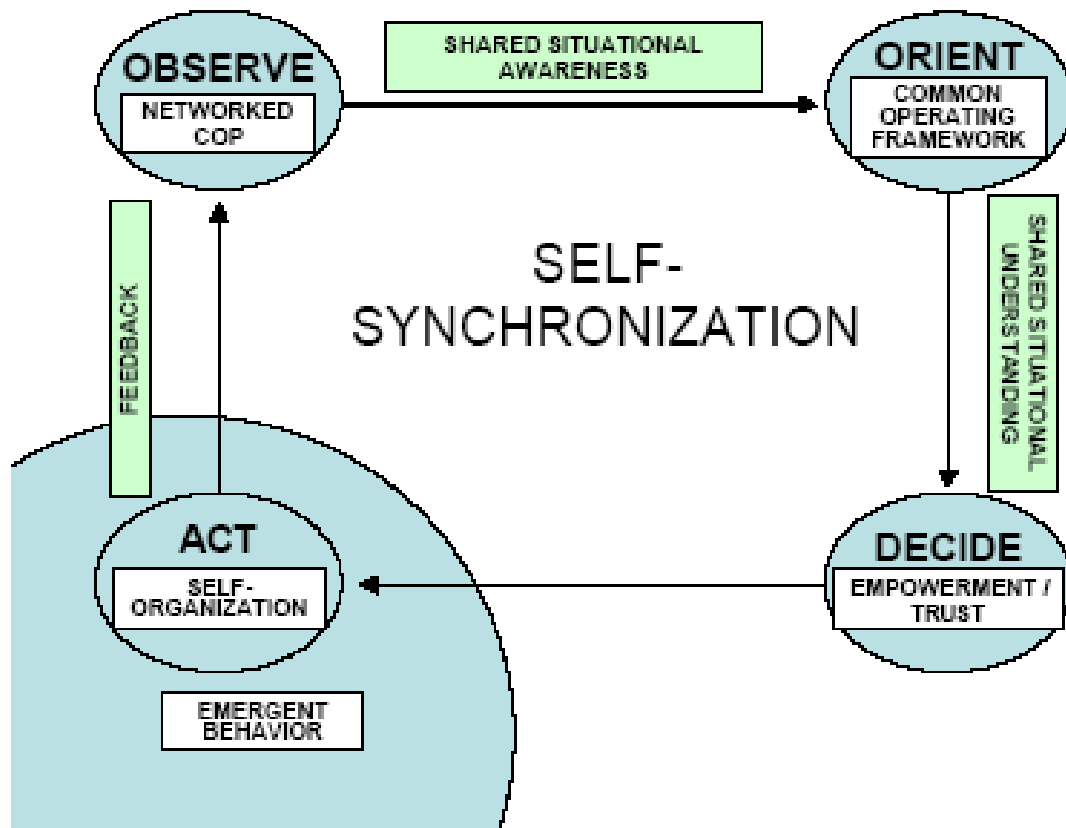


FIGURE 8: SELF-SYNCHRONIZATION REQUIREMENTS & BOYD'S OODA LOOP

“Self-synchronization”—
agents changing the nature
of their interaction with other
agents based on how they
“see” the local interactions
happening, and what they
see in the environment

Shared....What?

- Common Understanding
- Team Shared Awareness
- Shared Understanding
- Distributed Cognition
- Distributed Understanding
- Group Situational Awareness
- Shared Cognition
- Shared Visualization
- Team Awareness
- Coherent Tactical Picture

On Shared Situational Awareness*

- There are three elements in the development of a team's shared situational awareness.
 1. **Build** individual situational awareness.
 2. **Share** individual situational awareness. This is probably the most critical factor in creating shared awareness. It depends on effectively communicating each person's awareness, in order to build a shared mental model from the individual mental models.
 - so that a "consensus flow" develops
 3. **Develop** the group's shared situational awareness. This is the integration of the different individual mental models of the situation. Note that there need not be a single "team mental model." Multiple mental models can exist among team members but the models must overlap sufficiently to make it possible to perform the mission.
 - (A mental model is a "psychological representation of the environment and its expected behavior.")

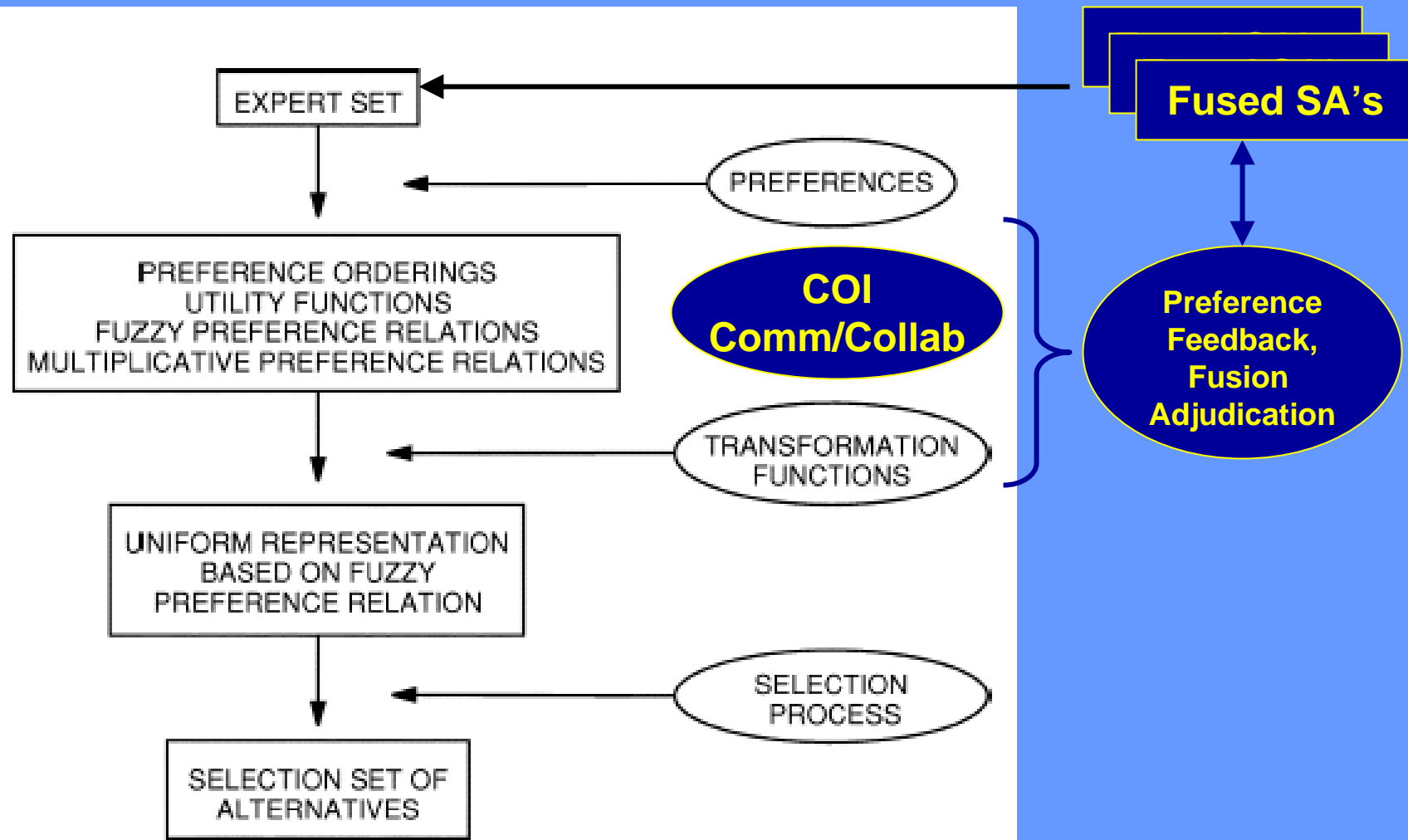
Communities of Interest (COL)

“The Cols are **collaborative groups of users** who must exchange information in pursuit of their shared goals, interests, missions, or business processes, and who therefore must have **shared definitions for the information they exchange**. Communities provide an organization and maintenance construct for data, operational processes and mission capabilities, providing boundaries to group information and functions relevant to the Col. Cols may be composed of members from one or multiple functions and organizations. **Institutional Cols**, whether functional or cross-functional, tend to be continuing entities with responsibilities for ongoing operations. They also lend support to contingency and crisis operations. **Expedient Cols** are more transitory and ad hoc, focusing on contingency and crisis operations. In all cases, the information and the functions that operate on it are bounded by the Col. This implies a tighter coupling of information and functions within a Col, and a looser coupling between Cols. “

Consensus of Meaning in COI's

- COI's are distinguished by being a group having heterogeneous expertise
- Hence, the basic issue for collaboration across different domains of expertise is the fact that **different experts will construct different meaning from the same situation**, based upon their relative knowledge and experience.
- Synthesizing a **Consensus Meaning** requires interaction of Data Fusion Service processes with the overall Collaboration Framework for the COI, regarding:
 - Identification and exchange of Boundary Objects
 - Monitoring of and adjustment to conflicts in Belief
 - Metrics for degree of Disagreement
- Applicable Theories
 - Social choice theory
 - Consensus theories (various)—Influence Networks
 - Notions of Preference
 - Belief Revision
 - Reinforcement Learning

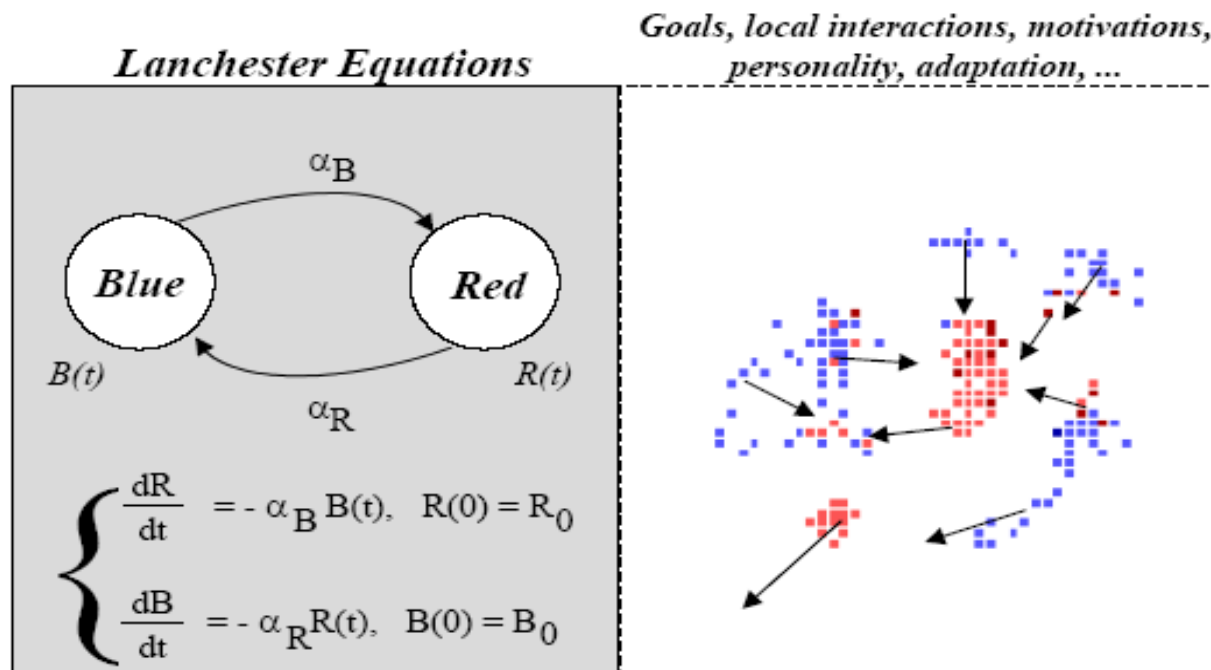
Representative Consensus Model for Multiperson Decision Making*



* E. Herrera-Viedma, "A Consensus Model for Multiperson Decision Making With Different Preference Structures", IEEE Trans. SMC Pt A: Systems and Humans, 32, NO. 3, May 2002

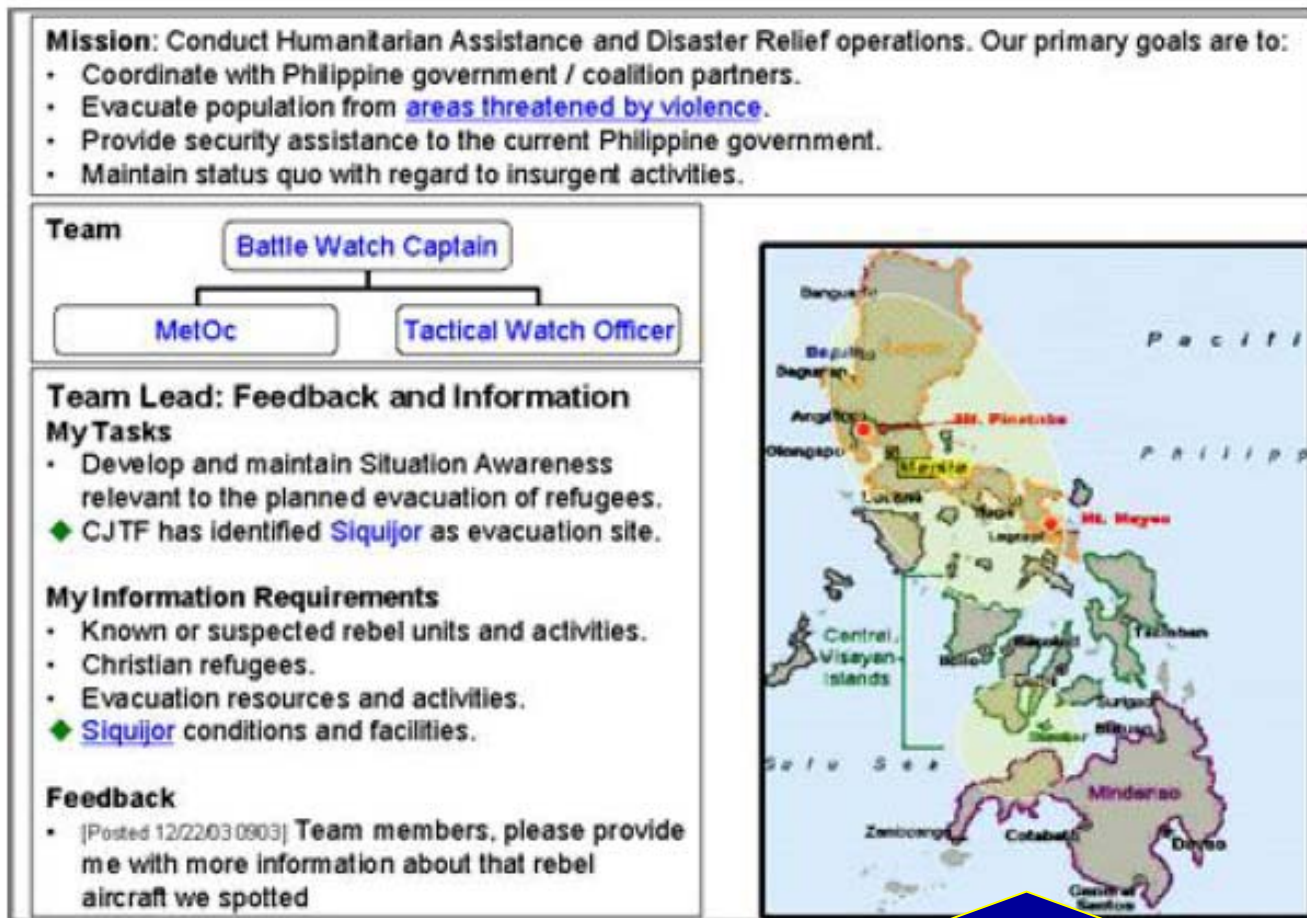
Traditional and Agent-based Research*

Lanchester vs *Agent-Based Models*



* A. Ilachinski, briefing on Einstein simulation environment

Sharing Context *



Mission

Organ Setting

Identity

Tasks

Info Needs

Guidance

DF Service